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(54) METHOD AND APPARATUS FOR MEASURING THICKNESS OF METAL LAYER

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(57) **ABSTRACT**

Disclosed are a method and apparatus for measuring a thickness of a metal layer formed on a semiconductor substrate. First, second, and third light pulses are successively irradiated onto a top surface of the metal layer to generate respective first, second, and third second sonic waves in the metal layer. Interference between the first and second sonic waves alters a detected reflectivity of the third light pulse off the metal layer. Maximum interference of the sonic waves occurs where the first sonic wave travels to a bottom surface of the metal layer and back to the top surface in the same time that it takes for the second light pulse to arrive at the surface of the metal layer. Accordingly, the velocity of the first sonic wave and a time lag between the first and second light pulses are used to determine the thickness of the metal layer.

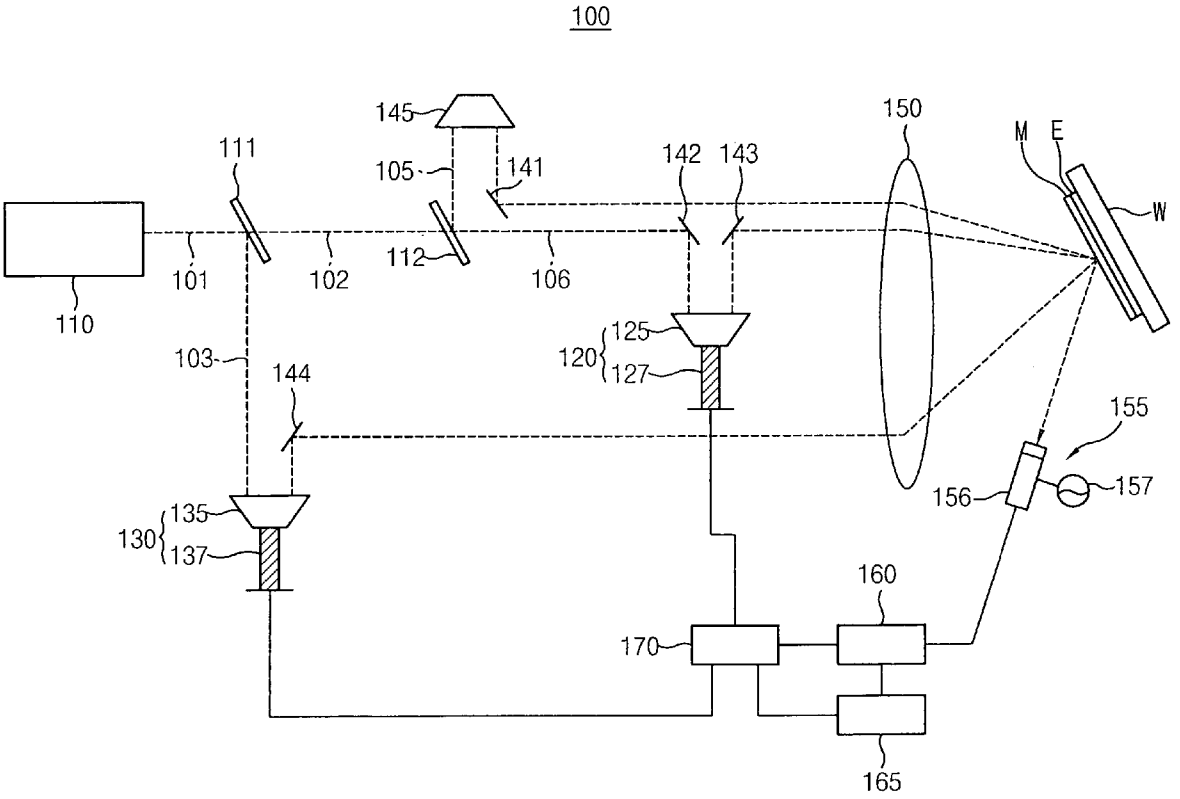
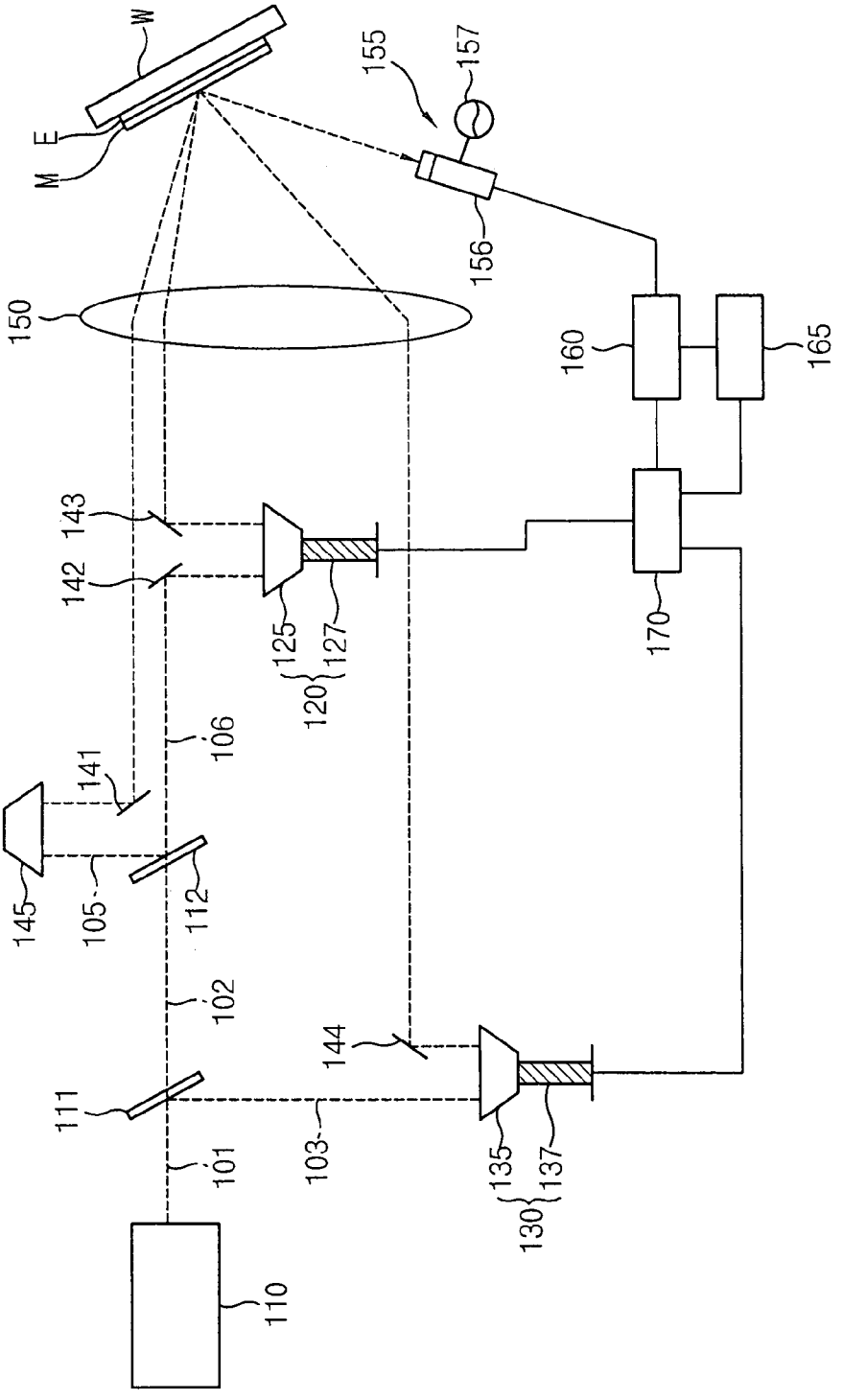


FIG. 1


100
W
M
E
155
157
156
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165
143
142
125
127
120
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106
141
145
105
112
102
144
111
103
101
135
137
130
110

FIG. 2

FIG. 3

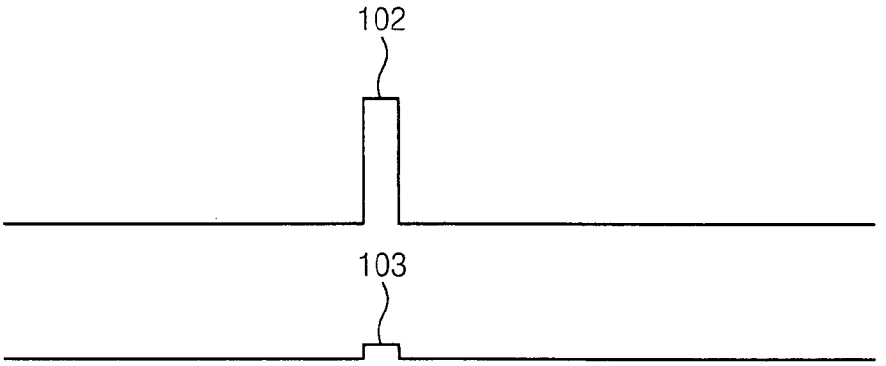


FIG. 4

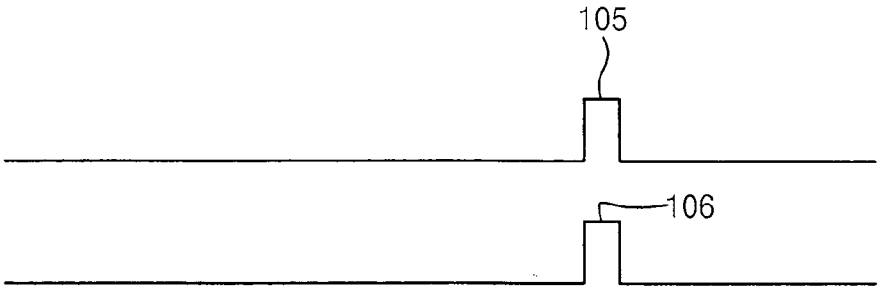


FIG. 5

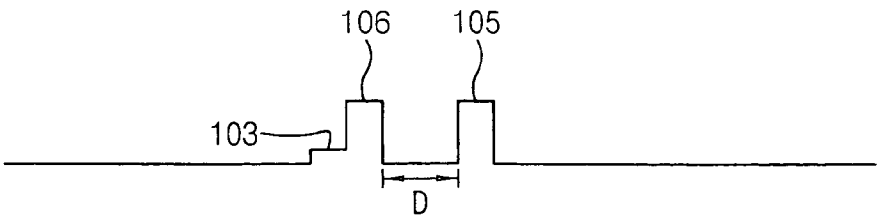


FIG. 6

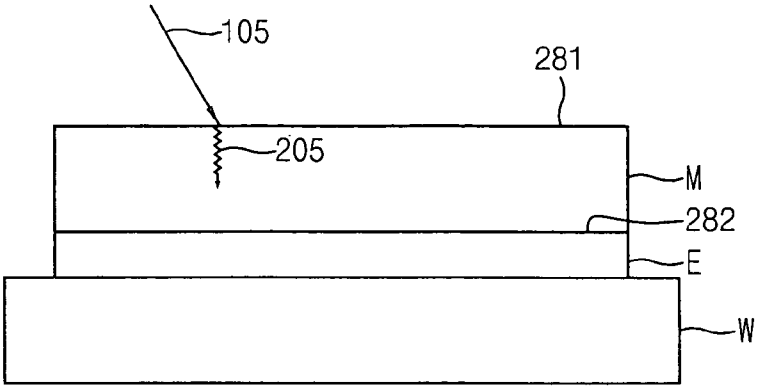


FIG. 7

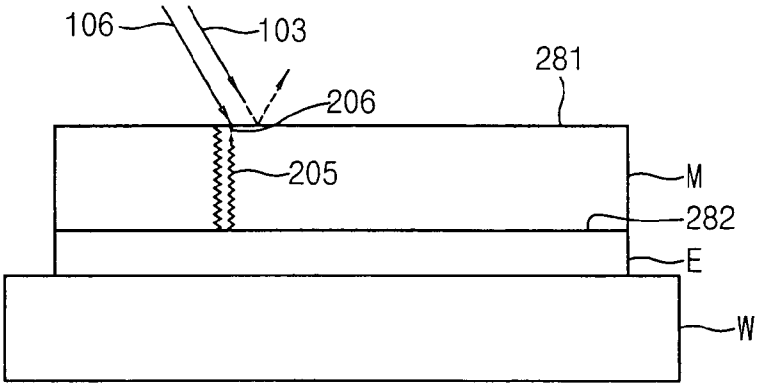


FIG. 8

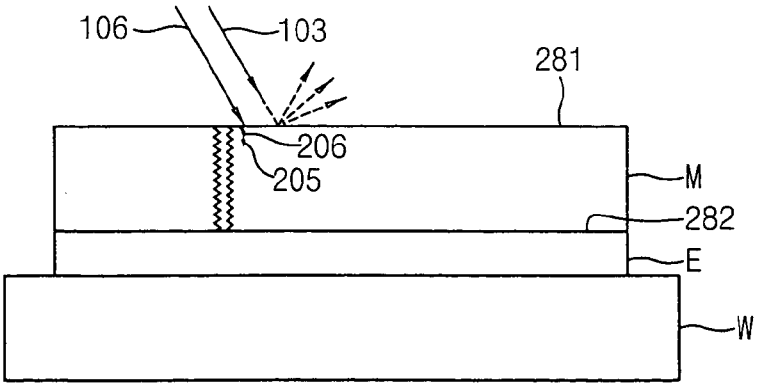


FIG. 9

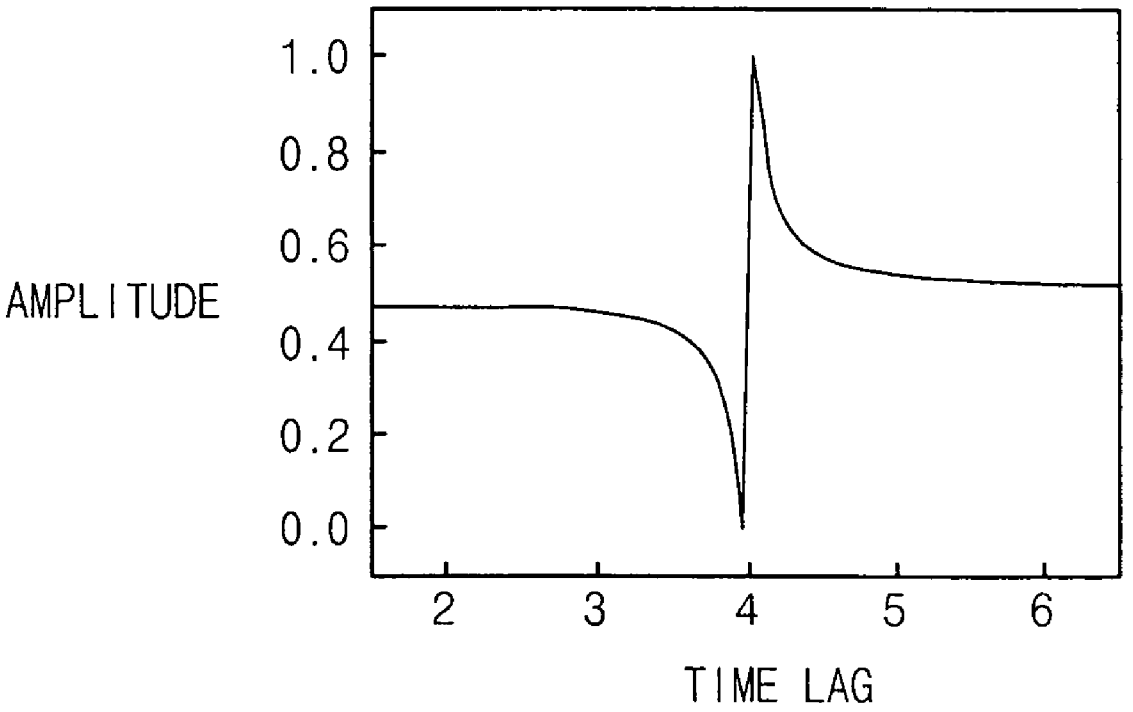
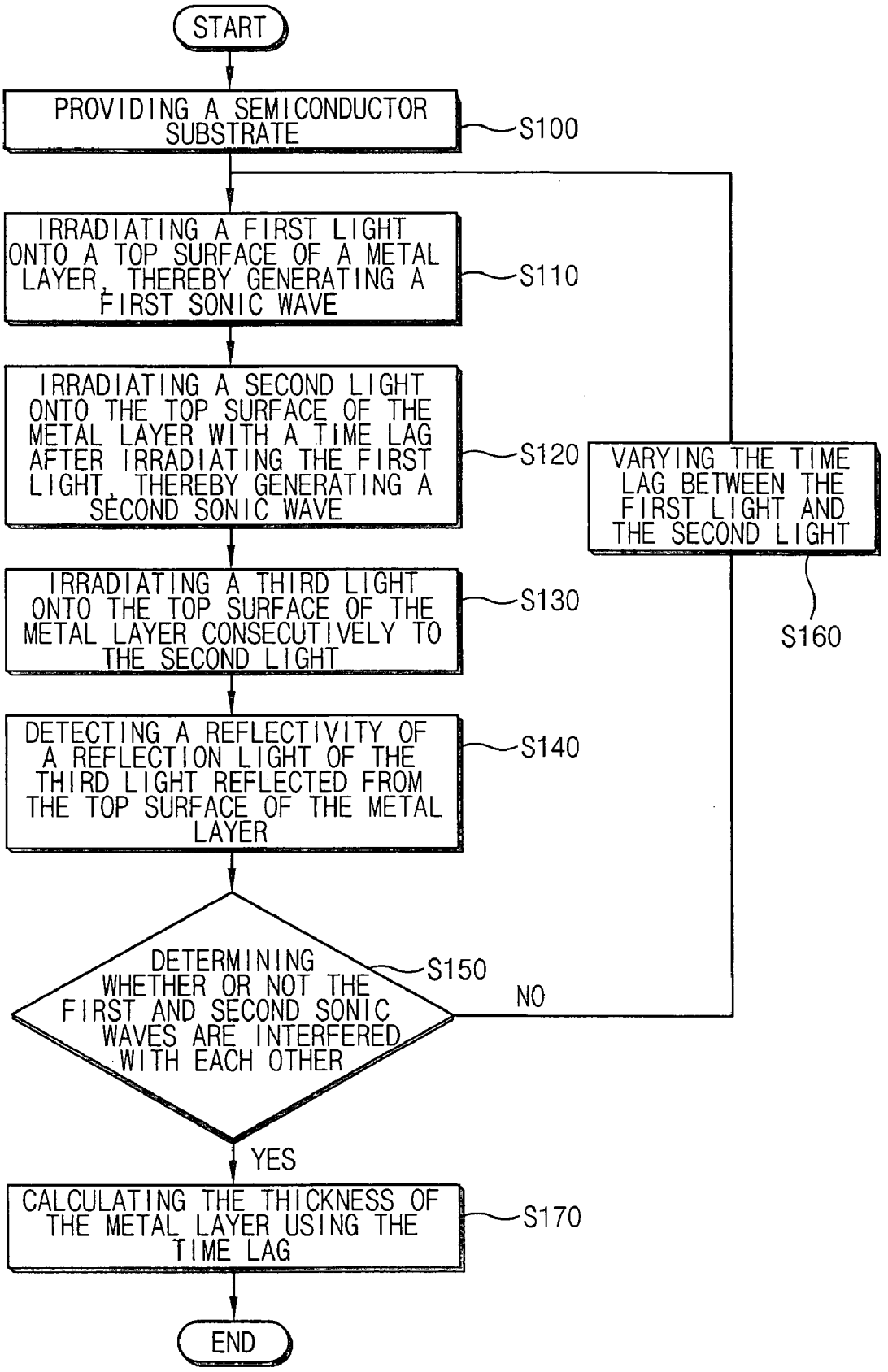


FIG. 10


START
PROVIDING A SEMICONDUCTOR SUBSTRATE
S100
IRRADIATING A FIRST LIGHT ONTO A TOP SURFACE OF A METAL LAYER, THEREBY GENERATING A FIRST SONIC WAVE
S110
IRRADIATING A SECOND LIGHT ONTO THE TOP SURFACE OF THE METAL LAYER WITH A TIME LAG AFTER IRRADIATING THE FIRST LIGHT, THEREBY GENERATING A SECOND SONIC WAVE
S120
IRRADIATING A THIRD LIGHT ONTO THE TOP SURFACE OF THE METAL LAYER CONSECUTIVELY TO THE SECOND LIGHT
S130
DETECTING A REFLECTIVITY OF A REFLECTION LIGHT OF THE THIRD LIGHT REFLECTED FROM THE TOP SURFACE OF THE METAL LAYER
S140
DETERMINING WHETHER OR NOT THE FIRST AND SECOND SONIC WAVES ARE INTERFERED WITH EACH OTHER
S150
NO
VARYING THE TIME LAG BETWEEN THE FIRST LIGHT AND THE SECOND LIGHT
S160
YES
CALCULATING THE THICKNESS OF THE METAL LAYER USING THE TIME LAG
S170
END

METHOD AND APPARATUS FOR MEASURING THICKNESS OF METAL LAYER

BACKGROUND OF THE INVENTION

[0001] 1. Field of the Invention

[0002] The present invention relates generally to a method and apparatus for measuring a thickness of a metal layer. More particularly, the present invention relates to a method and apparatus for measuring a thickness of a metal layer formed on a semiconductor substrate using a laser beam irradiated onto a surface of the metal layer.

[0003] A claim of priority is made to Korean Patent Application No. 2004-62816 filed on Aug. 10, 2004, the disclosure of which is hereby incorporated by reference in its entirety.

[0004] 2. Description of the Related Art

[0005] The performance of semiconductor devices is determined, at least in part, by the size and density of processing elements formed on the devices. For example, semiconductor devices with smaller, more densely formed processing elements generally achieve higher performance (e.g., throughput, data access speed, clock rate, etc.) than semiconductor devices having larger, less densely formed processing elements. Accordingly, considerable effort has been invested in developing methods of manufacturing semiconductor devices with smaller, more densely formed processing elements.

[0006] The manufacture of modern semiconductor devices typically includes several processing steps including various chemical and/or photographic processing steps, as examples. In the processing steps, various layers are typically formed on a semiconductor substrate and then etched to form processing elements.

[0007] In order to decrease the size (i.e., the critical dimension) of the processing elements, it is generally necessary to decrease the thickness of the layers formed on a semiconductor substrate. As the thickness of the layers decreases, an aspect ratio (i.e., width/height) of patterns formed on the substrate tends to increase as well. In addition, as the thickness of the layers decreases, inspection processes used to evaluate characteristics of the layers or patterns formed thereon become increasingly important.

[0008] Various devices such as a scanning electron microscope (SEM), a transmission electron microscope (TEM), a secondary ion mass spectrometer (SIMS), an X-ray fluorescence spectroscope (XRF) and an X-ray reflectometer (XRR) have been used to perform inspections on thin layers in the past. For example, U.S. Pat. No. 4,510,573 discloses an XRF, and U.S. Pat. No. 5,778,039 discloses a method and apparatus for inspecting a surface of a semiconductor substrate using the XRF. U.S. Pat. No. 6,453,006 discloses an XRR.

[0009] As explained previously, semiconductor devices are typically crated by forming several layers on a semiconductor substrate. In order to avoid producing defects in the semiconductor device, certain characteristics of the layers such as uniformity of doping concentration and thickness need to be carefully regulated. Accordingly, inspection processes are commonly performed to detect defects, irregularities, or non-uniformities on surfaces of the layers.

[0010] A titanium nitride layer is commonly utilized as a barrier layer in forming electrical devices such as transistors or capacitors or in forming a metal wiring. The thickness of the titanium nitride layer is generally very small. For example, in a flash memory device, the titanium nitride layer is formed to an even thickness of about 50 Å.

[0011] Unfortunately conventional inspection methods and apparatuses fail to properly inspect very thin layers because they lack the required resolution. In other words, they are not precise enough. Accordingly, new inspection methods and apparatuses are needed. In particular, improved methods and apparatuses are needed to inspect metal layers whose thickness is less than that of a dielectric layer formed on the semiconductor substrate.

SUMMARY OF THE INVENTION

[0012] According to one embodiment of the invention, a method of measuring a thickness of a metal layer formed on a semiconductor substrate is provided. The method comprises (a) sequentially irradiating a first light pulse, a second light pulse, and a third light pulse onto a top surface of the metal layer, and (b) detecting an intensity of the third light pulse reflected off the top surface of the metal layer. The method further comprises repeating (a) and (b) with a varying time lag between the first and second light pulses to discover a particular value of the time lag producing interference between first and second sonic waves generated in the metal layer by the respective first and second light pulses. The method further comprises determining the thickness of the metal layer using the particular value of the time lag. According to another embodiment of the present invention, an apparatus adapted to determine a thickness of a metal layer on a semiconductor substrate is provided. The apparatus comprises a light generator adapted to generate first, second, and third light pulses irradiated on a surface of the metal layer, a light receiver adapted to detect an intensity of the third light pulse reflected off the top surface of the metal layer, and a controller adapted to vary a time lag between the first and second light pulses. The method further comprises a determining unit adapted to determine the thickness of the metal layer using a particular value of the time lag producing interference between sonic waves generated in the metal layer by the first and second light pulses.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] The invention is described below in relation to several embodiments illustrated in the accompanying drawings. Throughout the drawings like reference numbers indicate like exemplary elements, components, or steps. In the drawings:

[0014] Figure (FIG.) **1** is a diagram illustrating an apparatus adapted to measure a thickness of a metal layer formed on a semiconductor substrate according to one embodiment of the invention;

[0015] **FIGS. 2 through 5** are signal diagrams showing relative intensities and timings for light pulses shown in **FIG. 1**;

[0016] **FIG. 6** is a diagram showing a first sonic wave generated in a metal layer by a first light pulse;

[0017] **FIG. 7** is a diagram showing destructive interference generated by interaction between first and second sonic waves in a metal layer;

[0018] **FIG. 8** is a diagram showing constructive interference generated by interaction between first and second sonic waves in a metal layer;

[0019] **FIG. 9** is a graph showing relative amplitudes of molecular vibrations on a top surface of a metal layer as a function of a lag time between first and second light pulses irradiated on the top surface; and,

[0020] **FIG. 10** is a flow chart illustrating a method of measuring a thickness of a metal layer formed on a semiconductor substrate according to an embodiment of the present invention.

DESCRIPTION OF THE EMBODIMENTS

[0021] Exemplary embodiments of the invention are described below with reference to the corresponding drawings. These embodiments are presented as teaching examples. The actual scope of the invention is defined by the claims that follow.

[0022] **FIG. 1** is a diagram of an apparatus **100** adapted to measure a thickness of a metal layer "M" formed on a semiconductor substrate "W" according to an embodiment of the present invention.

[0023] Referring to **FIG. 1**, apparatus **100** comprises a light source **110**, first and second splitters **111** and **112**, and first and second path regulators **120** and **130**. Apparatus **100** further comprises first through fourth mirrors **141**, **142**, **143** and **144**, a condenser lens unit **150**, a light receiver **155**, a storage unit **160**, a determining unit **165**, and a controller **170**.

[0024] First path regulator **120** typically comprises a first prism **125** and a first driver **127**, and second path regulator **130** comprises a second prism **135** and a second driver **137**. Apparatus **100** also comprises a third prism **145**. Alternatively, another optical element, such as a pair of mirrors, can be used in place of any of first, second, and third prisms **125**, **135**, and **145**. Light receiver **155** comprises a detector **156** and a power supply **157**.

[0025] Semiconductor substrate "W" is positioned adjacent to condenser lens unit **150**. A variety of layers are typically formed on semiconductor substrate "W". For instance, **FIG. 1** shows a dielectric layer "E" and metal layer "M" formed on semiconductor substrate "W". In order to measure the thickness of metal layer "M", however, metal layer "M" needs to be exposed to its surroundings. In other words, it should not be covered by another layer. Preferably, semiconductor substrate "W" is inclined at a predetermined angle with respect to condenser lens unit **150** so that light receiver **155** can be positioned to detect a light pulse reflecting off metal layer "M".

[0026] Light source **110** generates a source light pulse **101**. First splitter **111** is positioned in an optical path of source light pulse **101** to split source light pulse **101** into a preliminary light pulse **102** and a third light pulse **103**. Second splitter **112** is positioned in an optical path of preliminary light pulse **102** to split preliminary light pulse **102** into a first light pulse **105** and a second light pulse **106**. In sum, source light pulse **101** is split into first, second, and third light pulses **105**, **106**, and **103** by first and second splitters **111** and **112**.

[0027] Source light pulse **101** is preferably split into preliminary light pulse **102** and third light pulse **103** such that preliminary light pulse **102** has a luminous flux (hereafter, flux) of about 85 to 95 lumens (lm) and third light pulse **103** has a flux of about 5 to 10 lm. Preliminary light pulse **102** is split into first light pulse **105** and second light pulse **106** such that first light pulse **105** has a flux of about 50 to 60 lm and second light pulse **106** has a flux of about 40 to 60 lm.

[0028] The ratio of the fluxes of first, second, and third light pulses **105**, **106** and **103** is preferably about 45:45:10. Although the embodiment described above uses first and second splitters **111** and **112** to generate first, second and third light pulses **105**, **106** and **103**, these light pulses could also be generated by other techniques known to those skilled in the art. For example, first, second and third light pulses **105**, **106** and **103** could be generated by independent light sources.

[0029] Third prism **145** is positioned in an optical path of first light pulse **105** so as to refract first light pulse **105** at least twice, thereby changing its optical path. First mirror **141** is positioned in the optical path of first light pulse **105** downstream from third prism **145**. First mirror **141** reflects light pulse **105** toward condenser lens unit **150**.

[0030] Second mirror **142** is positioned in an optical path of second light pulse **106** so as to reflect its optical path toward first prism **125**. First prism **125** then refracts second light pulse **106** at least twice to change its optical path. Third mirror **143** is positioned in the optical path of second light pulse **106** downstream from first prism **125** to reflect second light pulse **106** toward condenser lens unit **150**.

[0031] Second prism **135** is positioned in an optical path of third light pulse **103**. Second prism **135** refracts third light pulse **103** at least twice to change its optical path. Fourth mirror **144** is positioned in the optical path of third light pulse **103** downstream from second prism **135**. Fourth mirror **144** reflects third light pulse **103** toward condenser lens unit **150**.

[0032] First, second, and third light pulses **105**, **106**, and **103** are focused at a point on a surface of metal layer "M" through condenser lens unit **150**. Preferably, source light pulse **101** has sufficient energy to heat a top surface of metal layer "M", thereby generating a sonic wave from the top surface of metal layer M. Specific properties of source light pulse **101** are chosen based on a particular type of metal layer M. For example, according to one embodiment, source light pulse **101** is chosen to be an ultra-short wave, high-energy laser beam pulse with a pulse width of a few picoseconds.

[0033] First prism **125** is supported by first driver **127**. First driver **127** is controlled by controller **170** to adjust its location, thereby changing a distance between first prism **125** and second and third mirrors **142** and **143**. Changing the distance between first prism **125** and second and third mirrors **142** and **143** alters a distance traveled by second light pulse **106** between second mirror **142** and third mirror **143**. As examples, first driver **127** can move first prism **125** away from second and third mirrors **142** and **143** to increase the distance traveled by second light pulse **106**. Likewise, first driver **127** can move first prism toward second and third mirrors **142** and **143** to decrease the distance traveled by second light pulse **106**.

[0034] Second prism **135** is supported by second driver **137**. Second driver **137** is controlled by controller **170** to adjust its location, thereby changing a distance between second prism **135** and second and fourth mirror **144**. Changing the distance between second prism **135** and fourth mirror **144** alters a distance traveled by third light pulse **103** between first splitter **111** and mirror **144**.

[0035] Changing the distance traveled by second and third light pulses **106** and **103** causes second and third light pulses **106** and **103** to arrive at condenser lens unit **150** at different times. Accordingly, the relative timing of first, second, and third light pulses **105**, **106**, and **103** is readily altered by altering the position of first and second prisms **125** and **137** using first and second drivers **127** and **137**. A relative time lag "D" between first light pulse **105** and second light pulse **106** is controlled by varying the distance between first prism **125** and second and third mirrors **142** and **143**.

[0036] First driver **127** may comprise any one of a number of driving units. For example, first driver **127** typically comprises a ball block including a lead screw, a transfer belt, and a stepper motor. An exemplary stepper motor is described briefly below.

[0037] The stepper motor is characterized by a precisely controlled revolution speed and revolution angle. The revolution angle of the stepper motor is proportional to a total number of light pulses that have passed through first prism **125** and the revolution speed of the stepper motor is proportional to a number of light pulses passing through first prism **125** each second. In other words, for each light pulse that passes through first prism **125**, the stepper motor rotates (i.e., steps) by a predetermined amount to increment the revolution angle. Hence, the cumulative revolution angle of the stepper motor is determined by the number of times that the revolution angle has been incremented and the revolution speed of the stepper motor is determined by the frequency of the increments. An error in the revolution angle is typically less than about 0.05° per step. However, the error is not accumulated with every step of the stepper motor.

[0038] The stepper motor requires no feedback to detect the revolution angle and it is operated in a relatively simple way. For instance, where source light pulse **101** has a pulse width of about 0.2 picoseconds and a velocity of about 3×10^8 m/s, the distance across source light pulse **101** is about 0.06 mm. The distance across source light pulse **101** is calculated by multiplying its velocity by its pulse width. In this case, the stepper motor is controlled in such a way that the revolution angle is incremented by about 0.06 mm, i.e., substantially the same as the distance across source light pulse **101** each time a light pulse passes through first prism **125**.

[0039] Preferably, first driver **127** includes a stepper motor having a radius of revolution in a range from about a few to a few dozen micrometers (μm). However, the revolution radius of the stepper motor can vary. In addition, first driver **127** may comprise any of various other driving means in accordance with time lag "D" between first light pulse **105** and second light pulse **106**.

[0040] Second driver **137** is substantially the same as first driver **127**. Accordingly, further description of second driver **137** is omitted to avoid redundancy. However, it should be noted that other means of changing the distance between second prism **135** and fourth mirror **144** may be used in place of second driver **137**.

[0041] **FIGS. 2 through 5** are signal diagrams showing relative intensities and timings for light pulses contained in the light s shown in **FIG. 1**. In particular, **FIG. 2** is a diagram of source light pulse **101**, **FIG. 3** is a diagram of preliminary light pulse **102** and third light pulse **103**, **FIG. 4** is a diagram of first and second light pulses **105** and **106**, and **FIG. 5** is a diagram of first, second, and third light pulses **105**, **106**, and **103** after being reflected by respective first, third, and fourth mirrors **141**, **143**, and **144**. As seen in **FIGS. 2 through 5**, the intensity (i.e., amplitude) of source light pulse **101** is roughly equal to a sum of the intensities of preliminary light pulse **102** and third light pulse **103**. The intensity of preliminary light pulse **102** is roughly equal to a sum of the intensities of first light pulse **105** and second light pulse **106**.

[0042] First, second and third light pulses **105**, **106** and **103** shown in **FIG. 5** are sequentially irradiated onto the top surface of metal layer "M". Second light pulse **106** is irradiated onto metal layer "M" following a predetermined time lag "D" after first light pulse **105** is irradiated onto metal layer "M". Third light pulse **103** is irradiated onto the top surface of metal layer "M" immediately after second light pulse **106**. Time lag "D" between first and second light pulses **105** and **106** is determined by a pulse width of source light pulse **101**. For example, where source light pulse **101** has pulse width of 0.2 picoseconds, time lag "D" between first and second light pulses **105** and **106** is controlled to be more than about 0.2 picoseconds.

[0043] **FIGS. 6 through 8** illustrate interactions between first through third light pulses **105**, **106**, and **103**, and metal layer "M". As shown in **FIGS. 6 through 8**, metal layer "M" is formed on a dielectric layer "E", which is formed on a semiconductor substrate "W". Metal layer "M" has a top surface **281** and a bottom surface **282**.

[0044] Referring to **FIG. 6**, where first light pulse **105** is irradiated onto top surface **281**, heat is generated on metal layer "M". The heat causes molecular distances between molecules in metal layer "M" to increase. Due to the increase of the molecular distances in metal layer "M", a first sonic wave **205** is generated in an upper portion of metal layer "M" near top surface **281**.

[0045] Referring to **FIG. 7**, where second light pulse **106** is irradiated onto top surface **281**, additional heat is generated on metal layer "M". The additional heat causes molecular distances between molecules in metal layer "M" to increase, causing a second sonic wave **206** to be generated in an upper portion of metal layer "M".

[0046] Similarly, where third light pulse **103** is irradiated onto top surface **281**, a third sonic wave is generated at an upper portion of metal layer "M" due to variations in the molecular distances of metal layer "M" caused by heat generated by third light pulse **103**. However, the intensity of third light pulse **103** is lower than that of first and second light pulses **105** and **106**, and as a result, the intensity of the third sonic wave is much lower than that of first and second sonic waves **205** and **206**. Accordingly, in at least one embodiment of the invention, the third sonic wave is not considered when measuring the thickness of metal layer "M". Instead, third light pulse **103** is only used for measuring molecular vibrations on top surface **281**.

[0047] Light receiver **155** is located at a position facilitating the detection of third light pulse **103** reflected from top

surface **281**. Light receiver **155** is preferably positioned in a space between condenser lens unit **150** and semiconductor substrate "W" and inclined at an angle with respect to the condenser lens unit **150**.

[**0048**] First and second light pulses **105** and **106** are also reflected from surface **281** of metal layer "M". However, light receiver **155** is positioned in such a way that third light pulse **103** is detected and first and second light pulses **105** and **106** are not detected. This can be explained as follows.

[**0049**] First, second and third light pulses **105**, **106** and **103** are irradiated onto different points on a surface of condenser lens unit **150**. The different points are positioned along the circumference of a circle whose center is coincident with a center of condenser lens unit **150** and whose size is less than that of condenser lens unit **150**. Although first, second, and third light pulses **105**, **106**, and **103** irradiate onto different points of condenser lens unit **150**, first, second and third light s **105**, **106** and **103** are irradiated onto a common point on top surface **281** of metal layer "M" after passing through condenser lens unit **150**. First, second, and third light pulses **105**, **106** and **103** are each reflected from surface **281** of the metal layer "M" in different directions due to the inclination of semiconductor substrate "W" with respect to condenser lens unit **150**. Accordingly, third light pulse **103** travels on a different optical path from first and second light pulses **105** and **106** after reflecting off of metal layer "M". Light receiver **155** is positioned in the optical path of third light pulse **103**, and therefore, third light pulse **103** is detected by light receiver **155**.

[**0050**] As explained previously, light receiver **155** comprises a detector **156** and a power supply **157**. Detector **156** detects third light pulse **103** after it is reflected off metal layer "M" and power supply **157** supplies power to detector **156**.

[**0051**] Detector **156** measures the intensity third light pulse **103** after it is reflected off metal layer "M". The measured intensity is then transformed into an electrical signal. In other words, the intensity of third light pulse **103** is transformed into a voltage proportional to the intensity of third light pulse **103**.

[**0052**] A ratio of the intensity of third light pulse **103** before and after it is reflected off metal layer "M" provides a measure of a reflectivity of metal layer "M". Detector **156** calculates the reflectivity of metal layer "M" by comparing the intensity of third light pulse **103** after it is reflected from top surface **281** of metal layer "M" with the intensity of third light pulse **103** before it is reflected from top surface **281**. The reflectivity of metal layer "M" is stored in storage unit **160** as digital data.

[**0053**] Where molecular vibrations in metal layer "M" are severe due to foreign turbulence, the reflectivity of metal layer "M" becomes low and most of third light pulse **103** is scattered on, rather than reflected from top surface **281** of metal layer "M", as illustrated in **FIG. 9**. In contrast, where molecular vibrations in metal layer "M" are relatively small, the reflectivity of metal layer "M" becomes relatively high and most of third light pulse **103** is reflected rather than scattered by top surface **281** of metal layer "M".

[**0054**] The reflectivity of metal layer "M" stored in storage unit **160** is transferred into determining unit **165**, and determining unit **165** determines whether or not the reflectivity is within a predetermined error range. Where the reflectivity is out of the predetermined error range, controller **170** controls first path regulator **120** to vary the distance between first prism **125** and second and third mirrors **142** and **143** in accordance with a preset program. Accordingly, time lag "D" between the first light pulse **105** and second light pulse **106** is changed as the interval is varied. At the same time, controller **170** also controls second path regulator **130** based on time lag "D".

[**0055**] Where the reflectivity of metal layer "M" is within the predetermined error range, determining unit **165** determines the thickness of metal layer "M" using the following equation (1):

$$t = \frac{D \times v}{2} \tag{1}$$

[**0056**] In equation (1), "t" denotes the thickness of metal layer "M", "D" denotes a particular value of time lag "D" between first light pulse **105** and second light pulse **106**, and "v" denotes a velocity of first sonic wave **205**. Intuitively, equation (1) can be understood as follows. Sonic waves **205** and **206** experience significant interference where first sonic wave **205** travels to bottom surface **282** of metal layer "M" and then back to top surface **281** of metal layer "M" before second light pulse **106** irradiates top surface **281** of metal layer "M". In other words, significant interference occurs where first sonic wave **205** travels a distance of 2t in a time period "D". Hence, 2t=D×v, as indicated by equation (1).

[**0057**] Time lag "D" between first light pulse **105** and second light pulse **106** is preferably larger than a pulse width of a the first and second light pulses **105** and **106**. For example, where first and second light pulses **105** and **106** each have pulse width of about 0.2 picoseconds, time lag "D" is preferably more than 0.2 picoseconds.

[**0058**] First and second light pulses **105** and **106** have a resolution capable of measuring the thickness of a thin metal layer "M". In general, the resolution of a light pulse (i.e., the size of the smallest feature that can be reliably measured by the light) is calculated by the following equation (2):

$$R = \frac{w \times v}{2} \tag{2}$$

[**0059**] In equation (2), "R" denotes a resolution of a light pulse, "w" denotes a pulse width of a light pulse, and "v" denotes a velocity of the light pulse. For example, where a laser beam containing a light pulse with a pulse width of about 0.2 picoseconds travels at a velocity of about 5000 m/s, the resolution of the light pulse is about 5 mm according to equation (2). Accordingly, where the thickness of metal layer "M" is expected to be less than about 5 mm, a light pulse in the laser beam can have a pulse width no more than about 0.2 picoseconds. In other words, in order to accurately measure the thickness of metal layer "M", source light pulse **101** needs to have a pulse width smaller than a thickness of metal layer "M".

[**0060**] As previously, mentioned, first light pulse **105** typically has a flux of about 50 to 60 lm and second light

pulse **106** typically has a flux of about 40 to 60 lm. Preferably, first light pulse **105** has the same flux as second light pulse **106**.

[**0061**] Where first light pulse **105** is irradiated onto top surface **281** of metal layer M, top surface **281** of metal layer "M" is heated up. As a result, molecules in an upper portion of metal layer "M" are excited and intermolecular distances are increased. The molecules collide with each other and vibrate in the upper portion of metal layer "M", creating sonic wave **205** therein. In a similar fashion, second sonic wave **206** is generated in the upper portion of metal layer "M" due to molecular vibrations caused by second light pulse **106**.

[**0062**] First sonic wave **205** passes through an inside of metal layer "M", and is reflected at bottom surface **282** of metal layer "M", where metal layer "M" makes contact with dielectric layer "E". First sonic wave **205** reflected by bottom surface **282** of metal layer "M" is referred to hereafter as a bottom-reflected first sonic wave **205**. First sonic wave **205** is reflected by bottom surface **282** because dielectric layer "E" has a different density from metal layer "M". In general, dielectric layer "E" could be replaced with another layer having a different density from metal layer "M".

[**0063**] Since second light pulse **106** irradiates metal layer "M" after time lag "D", second sonic wave **206** travels down through metal layer "M" while bottom-reflected first sonic wave **205** travels up through metal layer "M". Accordingly, sonic wave **206** meets with bottom-reflected first sonic wave **206** to create constructive or destructive interference.

[**0064**] Where sonic waves **205** and **206** interfere with each other constructively, the molecules in metal layer "M" vibrate more severely than without the interference. In contrast, where waves **205** and **206** interfere with each other destructively, the in metal layer "M" vibrate less frequently than without the interference. Interference occurring between first and second sonic waves **205** and **206** is described in further detail hereafter.

[**0065**] As shown in **FIG. 7**, second sonic wave **206** passes through metal layer "M" in a direction opposite to that of bottom-reflected first sonic wave **205**. As a result, where an intensity (i.e., an amplitude) of second sonic wave **206** is substantially the same as that of first sonic wave **205** and a phase of second sonic wave **206** is substantially opposite that of bottom-reflected first sonic wave **205**, bottom reflected first sonic wave **205** and second sonic wave **206** interfere destructively so that the molecular vibrations at the top surface portion of the metal layer "M" are remarkably diminished.

[**0066**] In order to form second wave **206** with the same intensity as first wave **205**, second light pulse **106** is required to have about the same flux as first light pulse **105**. Because wave energy of first sonic wave **205** is gradually dissipated as first sonic wave **205** passes through metal layer "M", second light pulse **106** is theoretically required to have slightly less flux than first light pulse **105** in order for perfect destructive interference to occur between first and second sonic waves **205** and **206**. However, in practice, the dissipated wave energy dissipation of first sonic wave **205** is insignificant because the thickness of metal layer "M" is very small. Accordingly, setting second light pulse **106** to have the same flux as first light pulse **105** is sufficient to cause destructive interference between bottom-reflected first sonic wave **205** and second sonic wave **206**.

[**0067**] After reflecting from bottom surface **282** of metal layer "M" and reaching top surface **281**, first sonic wave **205** is again reflected from top surface **281** of metal layer "M" and passes through metal layer "M" due to a density difference between metal layer "M" and its surroundings. First sonic wave **205** reflected from top surface **281** of metal layer "M" after reflecting from bottom surface **282** is referred to hereafter as a top-reflected first sonic wave **205**, in contrast to bottom-reflected first sonic wave **205**. As shown in **FIG. 9**, second sonic wave **206** passes in the same direction as top-reflected first sonic wave **205** to create constructive interference. As a result, molecular vibrations in metal layer "M" are remarkably reinforced.

[**0068**] Where third light pulse **103** is irradiated onto top surface **281** of metal layer "M" at the same time that bottom-reflected first sonic wave **205** and second sonic wave **206** cancel each other out due to destructive interference, a detected reflectivity of third light pulse **103** measured by detector **156** is remarkably high. In contrast, where third light pulse **103** is irradiated onto the top surface of the metal layer "M" at the time that top-reflected first sonic wave **205** and second sonic wave **206** are added to each other due to the constructive interference, the detected reflectivity of third light pulse **103** is remarkably low. Accordingly, a wide deviation in the detected reflectivity of third light pulse **103** from a baseline reflectivity indicates that first and second sonic waves **205** and **206** interfere with each other constructively or destructively in metal layer "M".

[**0069**] The baseline reflectivity is defined as a reflectivity measured by detector **156** while third light pulse **103** is irradiated onto top surface **281** and first sonic wave **205** passes through the inside of metal layer "M". In other words, the baseline reflectivity is defined as a reflectivity measured while first and second sonic waves **205** and **206** do not interfere with each other.

[**0070**] Where the detected reflectivity of third light pulse **103** deviates significantly from the standard reflectivity, bottom-reflected first sonic wave **205** or top-reflected first sonic wave **205** is interfering with second sonic wave **206** and time lag "D" between first light pulse **105** and second light pulse **106** corresponds substantially to the time for first sonic wave **205** to go to bottom surface **282** and return to top surface **281** of metal layer "M". The thickness of metal layer "M" can therefore be calculated by the following equation (3):

$$t = \frac{vD}{2} \tag{3}$$

[**0071**] In equation (3), "t" denotes the thickness of metal layer "M", "v" denotes the velocity of first sonic wave **205**, and "D" denotes time lag "D" between first light pulse **105** and second light pulse **106**. The velocity of first sonic wave **205** can vary significantly depending on a kind of the metal layer "M" and its physical properties.

[**0072**] An exemplary method of measuring the thickness of metal layer "M" is described below with reference to **FIG. 9**.

[0073] Referring to **FIG. 9**, the amplitude of molecular vibrations is graphed for values of time lag "D" ranging between one picosecond and six picoseconds. The amplitude of the molecular vibrations is shown in relative units in the graph.

[0074] Where time lag "D" is about 4 picoseconds, the amplitude of the molecular vibrations is remarkably increased from zero to about one. The remarkable increase of the molecular vibration amplitude indicates that first and second sonic waves **205** and **206** interfere with each other at top surface **281** of metal layer "M".

[0075] In this example, the velocity of first sonic wave **205** is about 5000 m/s and time lag "D" is about 4 picoseconds. Using equation (3), the thickness of metal layer "M" is calculated to be about 100 Å. Where time lag "D" is about 3.99 picoseconds, the amplitude of the molecular vibration is relatively small, and where time lag "D" is about 4.01 picoseconds, the amplitude of the molecular vibration is relatively large. Hence, a practical difference of about 0.02 picoseconds exists between values of time lag "D" resulting in minimum and maximum amplitudes of molecular vibrations.

[0076] Since the difference between time lags "D" resulting in the minimum and maximum amplitudes of molecular vibration is so small, the thickness of metal layer "M" can be measured using the time lag "D" corresponding to the minimum or maximum amplitude without significantly impairing the accuracy of the thickness measurement of metal layer "M". However, measuring the thickness of metal layer "M" using lag time "D" between the minimum and maximum amplitudes of molecular vibrations tends to increase the accuracy of the measurement.

[0077] While the above described exemplary embodiment discloses time lag "D" in a range between 1 and 6 picoseconds, time lag "D" preferably varies from about −10% to about +10% of a critical time lag "D". The critical time lag "D" is a value of time lag "D" at which molecular vibrations at the surface of metal layer "M" vary between the minimum point and a maximum point.

[0078] As described above, changing the distance traveled by second light pulse **106** varies time lag "D", and changing the distance traveled by third light pulse **103** ensures irradiation of third light pulse **103** onto top surface **281** of metal layer "M" immediately after irradiation by second light pulse **106**.

[0079] **FIG. 10** is a flow chart illustrating a method of measuring a thickness of a metal layer formed on a semiconductor substrate according to one embodiment of the invention. In this written description, method steps are designated by parentheses (Sxxx) to distinguish them from exemplary device or apparatus elements.

[0080] Referring to **FIG. 1**, semiconductor substrate "W" is provided to apparatus **100** to measure the thickness of metal layer "M" formed thereon (**S100**). First light pulse **105** is irradiated onto top surface **281** of metal layer "M", so that first sonic wave **205** is generated in the upper portion of metal layer "M" (step **S110**). Second light pulse **106** is irradiated onto top surface **281** of metal layer "M" following a predetermined time lag "D" after first light pulse **105** is irradiated on surface **281**. The irradiation of second light pulse **106** causes a second sonic wave **206** to be generated in the upper portion of metal layer "M" (step **S120**).

[0081] Third light pulse **103** is irradiated onto top surface **281** of metal layer "M" (step **S130**). Third light pulse **103** is reflected off of metal layer "M" and detected by detector **156**. Detector **156** calculates a reflectivity of metal layer "M" (step **S140**) based on detected third light pulse **103**. The reflectivity is then stored as digital data in storage unit **160**.

[0082] Determining unit **165** determines whether or not first and second sonic waves **205** and **206** interfere with each other in the upper portion of metal layer "M" (step **S150**). Time lag "D" is varied by changing the position of first driver **127** until first and second sonic waves **205** and **206** interfere with each other. Where first and second sonic waves **205** and **206** interfere with each other constructively or destructively, determining unit **165** calculates the thickness of metal layer "M" (step **S170**) using time lag "D" between first light pulse **105** and second light pulse **106**.

[0083] Where first and second sonic waves **205** and **206** do not interfere with each other, controller **170** controls first path regulator **120** to change the distance between first prism **125** and second and third mirrors **142** and **143**, thereby varying time lag "D" between first light pulse **105** and second light pulse **106**. Thereafter, steps **S110**, **S120**, **S130**, **S140** and **S150** are repeated until first and second sonic waves **205** and **206** interfere with each other.

[0084] According to the embodiments of the present invention described above, constructively or destructively interfering sonic waves are generated in a metal layer by varying a time lag between light s used to generate the sonic waves. Lag times generating minimally and maximally interfering sonic waves in the metal layer are then used to calculate the thickness of the metal layer. Using the methods and apparatus described above, precise and reliable measurements can be made.

[0085] The foregoing preferred embodiments are teaching examples. Those of ordinary skill in the art will understand that various changes in form and details may be made to the exemplary embodiments without departing from the scope of the present invention which is defined by the following claims.

What is claimed:

1. A method of measuring thickness of a metal layer formed on a semiconductor substrate, the method comprising:

(a) sequentially irradiating a surface of the metal layer with a first light pulse to generate a first sonic wave in the metal layer, a second light pulse to generate a second sonic wave in the metal layer, and a third light pulse;

(b) detecting intensity of a reflected portion of the third light pulse;

repeating (a) and (b) with a time lag between irradiation of the first and second light pulses;

determining a time lag value producing interference between the first and second sonic waves; and,

determining the thickness of the metal layer in relation to the time lag value.

2. The method of claim 1, wherein irradiating the first, second and third light pulses onto thz surface of the metal layer comprises:

irradiating the surface of the metal layer with the first light pulse;

thereafter, irradiating the surface of the metal layer with the second light pulse following the time lag; and,

immediately after irradiating the surface of the metal layer with the second light pulse, irradiating the surface of the metal layer with the third light pulse.

3. The method of claim 2, wherein the time lag between the first light pulse and the second light pulse is varied by changing the respective optical paths associated with the first and second light pulses.

4. The method of claim 2, wherein the third light pulse is controlled to irradiate on the surface of the metal layer immediately after the second light pulse by changing the respective optical paths associated with the second and third light pulses.

5. The method of claim 1, wherein the first and second light pulses are produced by a laser beam.

6. The method of claim 1, wherein the interference between first and second sonic waves comprises destructive interference.

7. The method of claim 1, wherein the interference between first and second sonic waves comprises constructive interference.

8. The method of claim 1, wherein the thickness of the metal layer is determined by the equation:

$$t = \frac{D \times v}{2}$$

wherein, "t" denotes the thickness of the metal layer, "v" denotes a velocity of the first sonic wave, and "D" denotes the time lag value.

9. An apparatus adapted to determine a thickness of a metal layer on a semiconductor substrate, the apparatus comprising:

a light generator adapted to irradiate a surface of the metal layer with first, second, and third light pulses;

a light receiver adapted to detect a portion of the third light pulse reflected from the surface of the metal layer;

a controller adapted to vary a time lag between the first and second light pulses; and,

a determining unit adapted to determine the thickness of the metal layer using a time lag value corresponding to interference between respective sonic waves generated in the metal layer by the first and second light pulses.

10. The apparatus of claim 9, wherein the light generator comprises a laser beam.

11. The apparatus of claim 9, wherein the light generator comprises:

a light source adapted to generate a source light pulse;

a first splitter adapted to split the source light pulse into a preliminary light pulse and the third light pulse;

a second splitter adapted to split the preliminary light pulse into the first light pulse and the second light pulse;

a first path regulator adapted to define a second optical path associated with the second light pulse, wherein the surface of the metal layer is irradiated with the second light pulse following a time lag with respect to the first light pulse; and,

a second path regulator adapted to define a third optical path associated with the third light pulse, wherein the surface of the metal layer is irradiated by the third light pulse immediately after the second light pulse.

12. The apparatus of claim 11, wherein the first path regulator comprises:

an optical element placed in the second optical path; and,

a driving unit adapted to adjust a position of the optical element to vary the second optical path.

13. The apparatus of claim 11, wherein the second path regulator includes:

an optical element placed in the third optical path; and,

a driving unit adapted to adjust a position of the optical element to vary the third optical path.

14. The apparatus of claim 12, wherein the optical element comprises a prism.

15. The apparatus of claim 13, wherein the optical element comprises a prism.

16. The apparatus of claim 9, wherein the light receiver comprises:

a detector adapted to detect the intensity of the reflected portion of the third light pulse; and,

a power supply adapted to provide power to the detector.

17. The apparatus of claim 9, further comprising:

a storage unit adapted to store a value associated with the intensity of the reflected portion of the third light pulse and a baseline intensity value.

18. The apparatus of claim 9, wherein the light generator comprises:

three independent light sources respectively generating the first, second, and third light pulses.

19. The apparatus of claim 11, further comprising:

a prism located in a first optical path downstream from the second splitter;

a first mirror located in the first optical path downstream from the prism;

a second mirror located in the second optical path downstream from the second splitter;

a third mirror located in the second optical path downstream from the first path regulator;

a fourth mirror located in the third optical path downstream from the second path regulator; and,

a condenser lens unit located between the first through fourth mirrors and the semiconductor substrate.

20. The apparatus of claim 19, wherein each of the first and second path regulators comprises:

a prism; and,

a driver comprising a stepper motor.

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